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Key Points:

- Apatite U-Th/He ages average 41.3 ± 4.8 Ma, biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages are 81–83 Ma in the eastern Bendeleben Mountains.
- Thermochronology and modeling show rapid Late Cretaceous to Eocene exhumation.
- Seward Peninsula normal faults are part of the Hope Basin extensional system.

Supporting Information:

- Readme
- Table S1

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Thermochronologic constraints on Late Cretaceous to Cenozoic exhumation of the Bendeleben Mountains, Seward Peninsula, Alaska

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Abstract In the Bendeleben Mountains, Seward Peninsula, mid-Cretaceous granites are exposed in an uplifted block bounded on its south side by an E-W striking normal fault. The Bendeleben fault has well-preserved scarps 4–7 m in height that offset Holocene moraines. Seismic activity, young normal faulting, and Quaternary basaltic volcanism are all evidence of active extension. South of the Bendeleben fault, there is a 3–4 km deep basin. Fifteen apatite (U-Th)/He ages from granitic samples of the footwall yield an Eocene weighted mean age of 41.3 ± 4.8 Ma. Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the country rock of the Bendeleben pluton are 81–83 Ma. In spite of the young fault scarps, HeFTy and Pecube thermal modeling results illustrate that rapid exhumation of the Bendeleben Mountains occurred in the Late Cretaceous–Eocene and slowed since the Oligocene. A weak age–elevation relationship of apatite He ages and a lack of correlation between age and distance from the fault indicate that exhumation was accomplished with minimal block rotation on a steeply dipping, long-lived normal fault. Timing of extension in the Seward Peninsula can be correlated with deformation in the offshore Hope Basin where seismic reflection lines document Early Tertiary large-magnitude normal faulting followed by minor post-Miocene reactivation. The faulting observed in the Bendeleben Mountains is part of an extensional system that spans a large portion of the Bering Strait region. The tectonic model proposed in previous studies suggests that clockwise rotation of the Bering block relative to North America is the cause of extensional deformation in western Alaska.

1. Introduction

The Bendeleben Mountains, located in central Seward Peninsula of the Bering Strait region of Alaska, are underlain by a normal fault block that exposes a Late Cretaceous granitic batholith surrounded by high-grade metamorphic rocks [Gottlieb and Amato, 2008; Harris et al., 2010; Till and Dumoulin, 1994]. Young normal fault scarps are well exposed along the southern flank of the Bendeleben range and along the north flank of the Kigluaik Mountains, located to the west (Figure 1), defining a fault system about 175 km long [Hudson and Plafker, 1978]. The lithologies and structural relief make this area an excellent target for constraining the timing and magnitude of exhumation using apatite helium (AHe) thermochronology, as has been done in other extensional settings [Ehlers et al., 2001; Stockli et al., 2003]. In this study, we use (U-Th)/He thermochronology of apatite from granitic samples collected in the Bendeleben Mountains, coupled with time–temperature (t–T) modeling implemented in Pecube [Braun, 2003] and HeFTy [Ketchum, 2005] to constrain the timing, duration, and intensity of exhumation events and to offer insight into the neotectonics of the Seward Peninsula and the Bering region (Figure 2).

Large magnitude extension and exhumation of high grade metamorphic rocks during the Cretaceous is documented in the Seward Peninsula [Amato et al., 1994; Dumitru et al., 1995; Miller et al., 1992], but the Tertiary to recent deformation history has received little attention. Hudson and Plafker [1978] first mapped the Bendeleben and Kigluaik normal faults and concluded that they accommodated large amounts of late Cenozoic displacement that resulted in the observed topographic and structural relief. However, Dumitru et al. [1995] using apatite fission-track thermochronology, showed that significant exhumation in the Kigluaik Mountains occurred not only in the late Cenozoic, but in the Eocene–Oligocene, along with tilting and several kilometers of local erosion, implying a longer history of normal faulting.



Figure 1. Location and simplified bedrock geologic maps of the Seward Peninsula after Till *et al.* [2011]. BP = Bendeleben pluton, IV = Imukuk volcanic field. Boxes in the Seward Peninsula map show the locations of Figure 5 (black) and Figures 3 and 11 (red). Fault symbols are solid where fault scarps are observed on satellite or aerial imagery, and dashed where the faults are inferred.

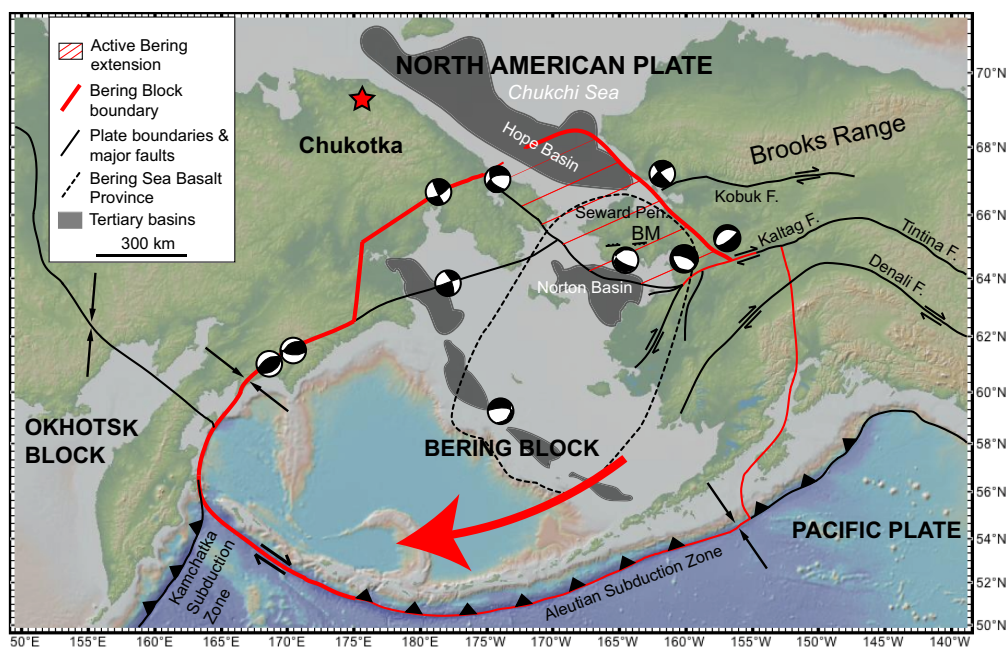


Figure 2. Neotectonic setting of the Bering block after Mackey *et al.* [1997] and Dumitru *et al.* [1995]. Selected focal mechanisms are lower-hemisphere projections with compressional quadrants colored black. Black arrows show the direction of relative motion across each plate boundary or fault. Red arrow shows rotation of the Bering block (outlined in red) relative to North American with Euler pole shown as a star. Hatched area in red represents the current N-S extensional system through the Seward Peninsula and the Hope Basin. Outline of the Bering Sea Basalt Province after Mull-Stalcup [1994]. BM = Bendeleben Mts., IV = Imukuk volcanic field.

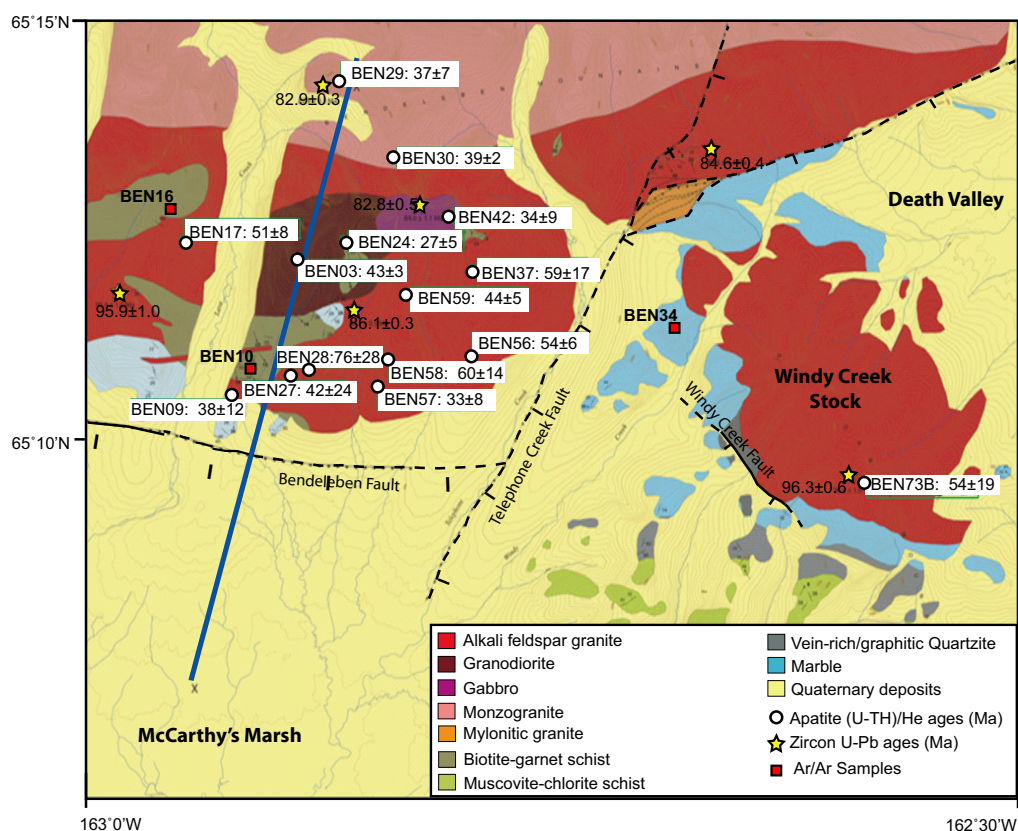


Figure 3. Geologic map of the eastern Bendeleben Mountains from Till *et al.* [2011] and Harris [2011] with locations of U-Pb, $^{40}\text{Ar}/^{39}\text{Ar}$, and AHe samples with respective ages and weighted mean error. Faults symbols are solid where scarps are observed and dashed where the fault is inferred. Location of figure is shown on Figure 1.

2. Geological and Tectonic Setting

The Seward Peninsula is part of the Arctic Alaska-Chukotka terrane, which includes the Brooks Range (northern Alaska), the Chukotka Peninsula (Russia), and large areas of the East Siberian and Bering continental shelf [Natal'in *et al.*, 1999] which accreted to North America in its current position after opening of the Arctic Basin [Grantz *et al.*, 1990]. During the Late Jurassic and Early Cretaceous, the Arctic Alaska-Chukotka terrane underwent arc-continent collision and partial subduction [Plafker and Berg, 1994; Till and Dumoulin, 1994], and subsequent granitic plutonism and metamorphism during a Cretaceous episode of extension and gneiss dome formation [Amato *et al.*, 1994; Miller *et al.*, 1992]. Since these events, there has been a progressive tectonic reorganization to a N-S extensional regime in western Alaska (Figure 2), as revealed by seismicity and young normal fault orientation [Biswas *et al.*, 1986; Dumitru *et al.*, 1995; Mackey *et al.*, 1997; Redfield *et al.*, 2007].

In east-central Seward Peninsula (Figure 3) low, rolling hills are underlain by Late Proterozoic and Early Paleozoic blueschist and greenschist facies schist and marble of the Nome Complex [Till *et al.*, 2011]. These rocks are locally covered by Tertiary deposits, such as the Imuruk Basin located north of the Kigluaik normal fault, and McCarthy's Marsh, south of the Bendeleben fault. The sedimentary succession in these basins may be similar to the section drilled by the Cape Espenberg 1 well, at the northernmost tip of the peninsula (Figure 1), which found 2450 m of volcanoclastic rocks overlain by nonmarine sandstone, siltstone and coal [Tolson, 1987].

The Bendeleben, Kigluaik, and the Darby Mountains (Figure 1) expose predominantly amphibolite grade gneisses, pelitic schists, quartzites, and marbles intruded by Cretaceous plutons [Till *et al.*, 2011]. The Bendeleben batholith is a composite granitoid body ranging in age from 104 to 82 Ma, with the younger rocks toward the east [Gottlieb and Amato, 2008; Harris, 2011]. The plutons in our (U-Th)/He study area have $^{238}\text{U}/^{206}\text{Pb}$ ages between 82.5 ± 0.9 and 95.7 ± 1.6 Ma [Harris, 2011]. The batholith varies in composition

from gabbro to biotite-rich alkali feldspar granite, is also variably deformed, and has a high strain mylonitic portion near its eastern end (Figure 3). At the intersection between the east-west trending Bendeleben Mountains and the north-south trending Darby Mountains there is a separate, smaller, alkali-feldspar granite, the Windy Creek pluton (Figure 3), which has a U-Pb age of 96.3 ± 0.6 Ma [Harris, 2011]. While sillimanite-facies schists flank the Bendeleben pluton, the country rock of the Windy Creek Pluton is greenschist facies. This abrupt change of metamorphic grade indicates that disparate structural levels are juxtaposed by the NE-SW trending Telephone Creek fault (Figure 3). The amount of strain varies along the Bendeleben Mountains with most intensely deformed rocks in the central section of the range [Gottlieb and Amato, 2008]. Miller and Bunker [1976] published a K-Ar biotite age of 81 ± 2 Ma from the Bendeleben pluton which agrees with our new data presented below and shows that the pluton cooled rapidly after emplacement to below the closure temperature for Ar in biotite. Like the Kigluaik gneiss dome to the west [Amato et al., 1994; Dumitru et al., 1995], and the Koolen gneiss dome across the Bering Straits in Russia, the Bendeleben metamorphic and plutonic complex is interpreted to have formed during a regional mid-Cretaceous extensional event [Gottlieb and Amato, 2008; Harris et al., 2010].

Late Cretaceous diabase dikes are found throughout the Seward Peninsula. In the Kigluaik Mountains, where they are best studied, the dikes yielded $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 84–81 Ma and predominantly strike 040° indicating a NW-SE direction of extension at that time [Amato et al., 2003].

During latest Cretaceous to Early Tertiary transpression along the southern continental margin of Alaska resulted in major dextral strike-slip displacements in Canada and the Alaskan interior along the Denali and Tintina fault systems (Figure 2) [Plafker and Berg, 1994]. The Kaltag fault, which terminates offshore in the Norton Basin, south of Seward Peninsula, is estimated to have 130 km of early to mid-Tertiary dextral offset [Lane, 1992; Patton and Hoare, 1968]. The Hope Basin, located offshore to the north of the Seward Peninsula, is at the termination of the Kobuk Fault. The Kobuk Fault is a major dextral structure in Alaska, although the amount of offset and timing of displacement is debated [Avé-Lallement et al., 1998]. The Hope Basin covers an area of roughly 75,000 km² in the Chukchi Sea and extends to the northwest as far as Wrangel Island [Elswick, 2003; Tolson, 1987]. Seismic reflection data [Elswick, 2003; Tolson, 1987] show the structure of the Hope Basin to be dominated by sets of tilted half-grabens, the deepest of which has as much as 5.8 km of sedimentary fill (Figure 4). Correlation with on-shore wells suggests that the basin fill ranges in age from at least Eocene to Late Pleistocene, although older strata may be present in the deepest grabens [Elswick, 2003]. The formation of these basins on the Bering Shelf has been attributed to a combination of tectonic extrusion along the major dextral strike slip faults and the retreat of the subduction zone from the southern edge of the Bering Shelf to the Aleutians during the Eocene [Plafker and Berg, 1994; Worrall, 1991].

Alkali-olivine and tholeiitic basalt flows cover an area in excess of 4600 km² north of the Bendeleben Mountains (Figure 1). We mention them here because of their possible impact on the thermal history of the area. Flows range from 28.8 Ma to Quaternary in age [Till and Dumoulin, 1994], but in the Imuruk volcanic field (Figure 2), $^{40}\text{Ar}/^{39}\text{Ar}$ data show that the major eruption took place between 6.03 ± 0.12 and 5.54 ± 0.05 Ma (total fusion ages) at a rate of approximately 70 ± 15 m³ km⁻² yr⁻¹ [Mukasa et al., 2007]. Some smaller flow fields occur in the Bendeleben Mountains in the vicinity of our sampling area (Figure 5). The Seward Peninsula basalts are part of the larger Bering Sea Volcanic Province (Figure 2), where most volcanism occurs in association with east-west striking normal faults [Moll-Stalcup, 1994].

3. The Bendeleben Fault

The Kigluaik and Bendeleben metamorphic domes are exposed due to uplift along their respective normal fault system (Figure 1). These normal faults are active, as revealed by current seismic activity [Fujita et al., 2002; Mackey et al., 1997] and by the fault scarps that are preserved along the southern flank of the Bendeleben Mountains and the northern flank of the Kigluaik Mountains where they offset Late Pleistocene lateral moraines [Hudson and Plafker, 1978; Kaufman et al., 1989] (Figure 5).

Small earthquakes (<4.0 M) are most common on the Seward Peninsula, although several ranging from 4.0 to 5.9, and one 6.0 to 6.9 M event have occurred [Fujita et al., 2002]. Focal mechanisms from Biswas et al. [1986] and Fujita et al. [2002] show the Seward Peninsula to be a region of N-S extension in recent time. Seismicity extends into the Chukotka Peninsula of Russia and outlines the edges of a rigid Bering Sea block (Figure 2) which is undergoing clockwise rotation probably as a response to terrane accretion in southeastern

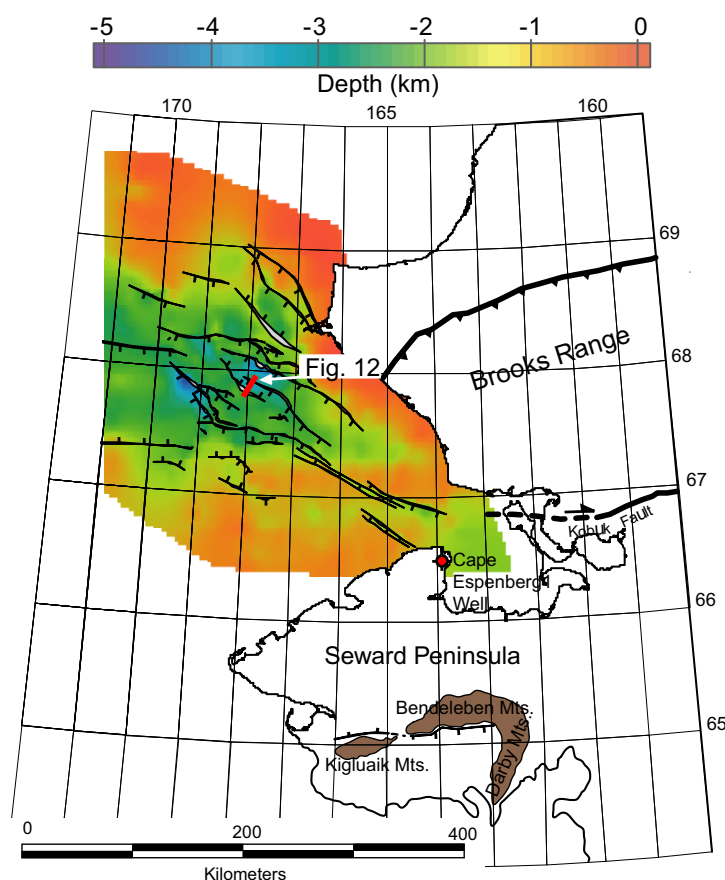


Figure 4. Depth to basement structural map of the Hope Basin with major faults [Elswick, 2003]. Red line shows the location of seismic line 801 (see Figure 12).

Alaska and tectonic extrusion along the Denali and Tintina strike-slip faults [Fujita *et al.*, 2002; Mackey *et al.*, 1997].

We estimate the Bendeleben fault to be about 100 km long, with down-to-the-south displacement and a curvilinear trace with average strike of 080 (Figures 1 and 5). The Kigluaik normal fault also strikes 080, is about 58 km long, but dips to the north and does not overlap with the Bendeleben fault.

They represent an approaching divergent conjugate pair, according to the normal fault classification of Morley *et al.* [1990], as the two fault tips do not merge or propagate past each other. Our mapping, based on aerial and satellite imagery, differs slightly from that of Hudson and Plafker [1978]. The Bendeleben fault scarp is visible from the vicinity of Mt. Bendeleben in the west, to near Telephone Creek in the east over about 60 km along the mountain front (Figure 5).

At the surface, the fault cuts

colluvium and glacial moraines. Amphibolite-grade pelitic schists, marbles, and granitoid rocks of the Bendeleben pluton are exposed close to the scarp on the footwall block. The youngest alluvial deposits along stream valleys are not visibly offset. The scarp ranges up to 8 m in height [Hudson and Plafker, 1978]. Near Lava Creek the scarp is approximately 4 m high with a 30° slope and some degradation. Dense vegetative cover exists on the scarp, including small shrubs, grasses, and trees (*Alder*, *Alnus sinuata*) ~3 m in height and up to 0.3 m in diameter at the base (Figures 5 and 6). The degree of vegetation and lack of displacement-effects on tree growth suggests very little historical fault activity. A second site west of Lava Creek has an observed scarp height of approximately 7 m. This segment of the fault dissects colluvium, as well as boulder fields and moraines with very steep scarp slopes that are highly degraded. Total post-Wisconsin displacement may be ~6–7 m on the central Kigluaik fault and 8 m on the central Bendeleben fault, as seen from displacements of Holocene lateral moraine deposits [Hudson and Plafker, 1978].

Although fault scarps are not observed east of Telephone Creek, there is structural evidence that faulting extends further east between the eastern termination of the Bendeleben and the northern end of the Darby Mountains [Harris, 2011]. An abrupt change in metamorphic grade from amphibolite facies to greenschist facies suggest that the Bendeleben fault is offset by a down-to-the-southeast, north-east striking fault along Telephone Creek. In addition, an extensive, albeit poorly exposed, high strain mylonite zone exists at the headwaters of Telephone Creek (Figure 3). The mylonite zone is aligned with the topographic break between the easternmost Bendeleben Mountains and the lowlands of Death Valley. We believe that this segment represents an older portion of the Bendeleben fault system, which has not been reactivated recently.

South of the Bendeleben Mountains lies the low fenland of McCarthy's Marsh. In order to estimate thickness of basin fill and to constrain total fault displacement, we modeled USGS Bouguer gravity data (Figures 6

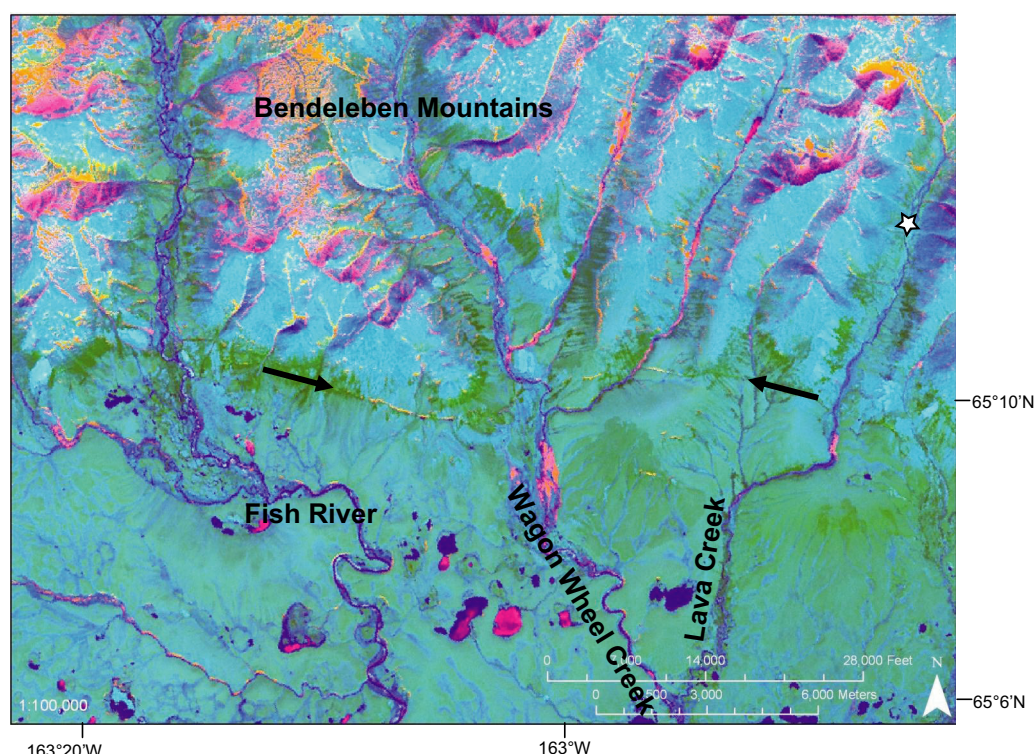


Figure 5. Enhanced PCA Landsat ETM image of the southeastern Bendeleben Mountains. Arrows point to the Bendeleben fault scarp. The star indicates the location of small Quaternary basalt flows in Lava Creek [Till *et al.*, 1986].

and 7). A negative gravity anomaly of approximately -60 mGals exists over the basin. Modeling in GM-SYS (Geosoft) suggests that the sedimentary basin fill is $\sim 3\text{--}4$ km thick, and is relatively symmetrical in cross section, not wedge shaped. Therefore, subsidiary faults stepping down to the basin bottom may exist. In addition, a superimposed, longer wavelength, anomaly of about -35 mGals extends across the Bendeleben Mountains and into the basalt fields on the north side. This anomaly has a poor correlation with topography indicating that it is not caused by a lower crustal root that supports the mountain range, but rather by a mass deficiency in the crust. The geographic overlap of the long-wavelength gravity low with the Late Cenozoic-Quaternary volcanic field north of the Bendeleben Mountains, and the high heat flow values in the area ($80\text{--}99$ mW m $^{-2}$) [Blackwell and Richards, 2004; Batir *et al.*, 2013], initially suggested to us that the gravity low may have a thermal origin. However, our models show that it would require a large body with a mass deficiency of -50 kg/m ^{3} , which requires too large of a temperature differential to be explained by thermal expansion of granitic crust (Figure 7). An alternative hypothesis is that the broad gravity low is caused by underplating of gabbroic material at the base of the crust that displaces mantle.

The steepest gravity gradient in the area is along the western flank of the Darby Mountains (Figures 1 and 6), suggesting the existence of a previously unrecognized major normal fault oriented orthogonally to the Bendeleben fault. We call this structure the Darby fault. Since this fault does not have scarps or an obvious geomorphic expression, it probably has not been reactivated in the current tectonic regime.

4. Thermochronology

4.1. $^{40}\text{Ar}/^{39}\text{Ar}$

We dated two biotite samples from sillimanite-grade pelitic schists of the footwall of the Bendeleben fault by the $^{40}\text{Ar}/^{39}\text{Ar}$ method (BEN10 and 16, location on Figure 3). Dr. Andrew Calvert carried out the analyses at the USGS geochronology laboratory in Menlo Park, CA. The complete analytical results are presented in the supporting information Table S1. Unfortunately both samples yielded disturbed spectra probably due to partial alteration of biotite to chlorite (Figure 8). Although the data are not ideal, they do place some useful constraints on the timing of cooling of the fault block below the Ar closure temperature of biotite, about

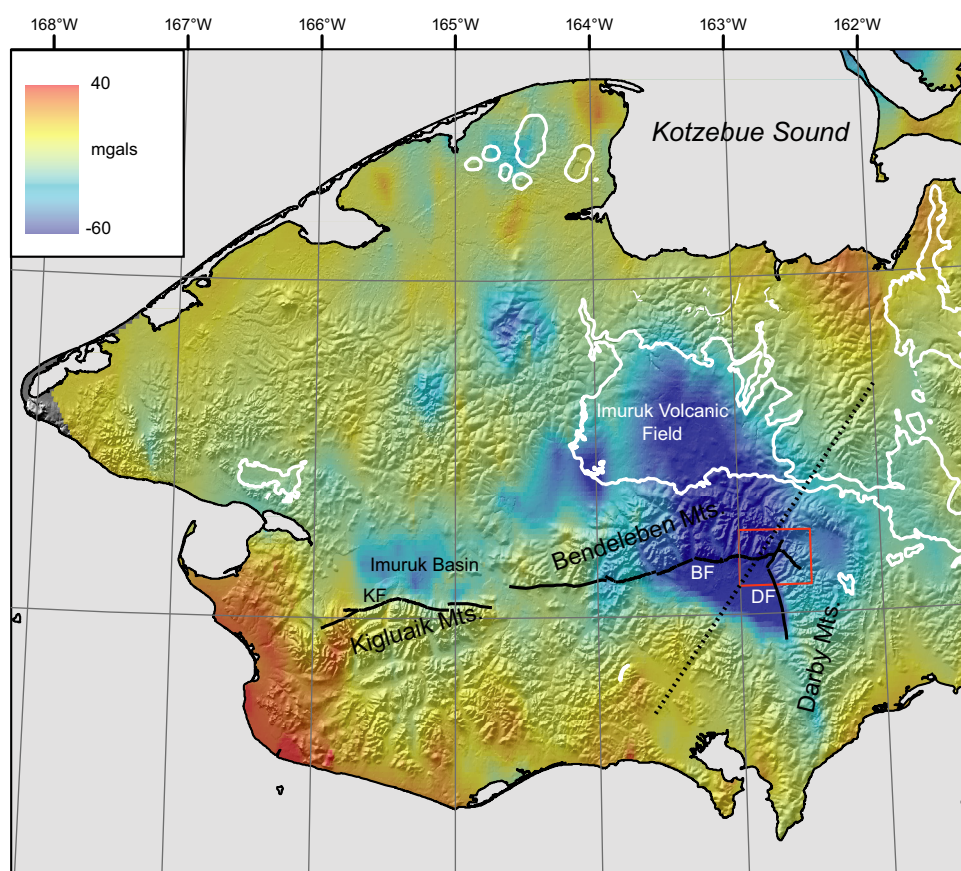


Figure 6. Bouguer gravity map gridded from USGS gravity data for NW Alaska [Saltus *et al.*, 2008]. Black lines are the major normal faults. Dotted black line is the gravity profile modeled in Figure 7. White line shows the outline of the major Cenozoic to recent basaltic fields from Till *et al.* [2011].

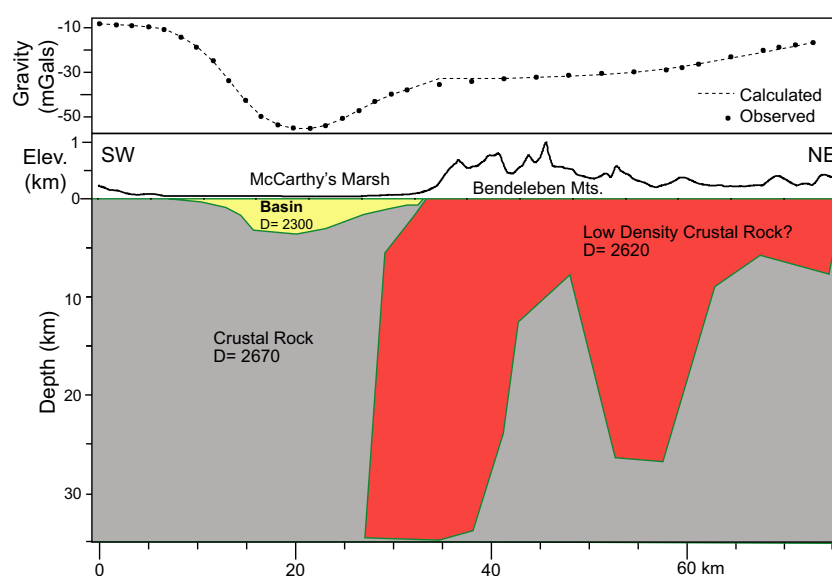


Figure 7. Gravity model (generated using GM-SYS) of USGS Bouguer gravity shown on Figure 6. The model suggests that the McCarthy's Marsh basin is 3–4 km deep. The longer wavelength gravity low requires a low-density body uncorrelated with the Bendeleben topography.

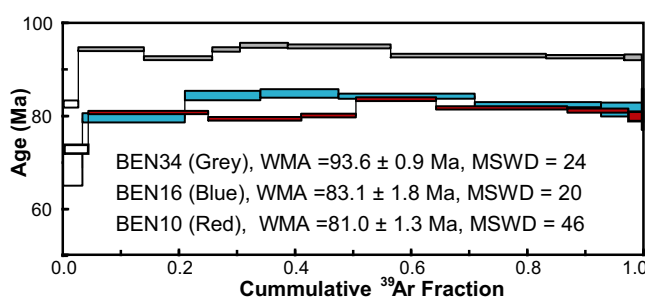


Figure 8. Biotite $^{40}\text{Ar}/^{39}\text{Ar}$ spectra from pelitic schist samples from the southeastern Bendeleben Mountains. See Figure 3 for locations. WMA=Weighted Mean Age for the colored portion of each spectrum.

persions of the individual ages, is 46. The isochron age calculated for this sample (81.5 ± 1.6 Ma) is concordant with the weighted mean age, and has a $^{40}\text{Ar}/^{36}\text{Ar}$ intercept (242 ± 60) that is within error of the expected atmospheric ratio indicating that there inherited Ar is not a problem. Sample BEN16 yielded a weighted mean age of 83 ± 2 Ma (MSWD=20) representing 96% of ^{39}Ar released. Individual age steps range from 79.5 to 84.7 Ma and do not overlap within their uncertainty either.

We collected a third sample, BEN34, from greenschist facies rock east of the Telephone Creek fault. It yielded a weighted mean age of 94 ± 1 Ma, representing 97% of released ^{39}Ar , with steps ranging from 92.4 to 95.1 Ma (Figure 8). In spite of the poor quality of our data, it is clear that the metamorphic rocks of the Bendeleben dome cooled below 350°C in the late Cretaceous not long after emplacement of the Bendeleben batholith.

4.2. (U-Th)/He

(U-Th)/He analysis of apatite has been demonstrated to be a useful tool for characterizing the low-temperature history and exhumation of upper crustal rocks, typically between depth of 1–4 km [Ehlers and Farley, 2003; House et al., 1998]. Ages of samples collected from the exhumed footwall of a normal fault can reveal the cooling history for the fault block. However, factors that negatively impact age patterns along the footwall block can include low footwall relief, upper crust thermal perturbations (ie. fluid flow and lateral heat advection across fault blocks), and rapid uplift with low footwall tilt [Braun, 2002; Ehlers, 2005].

We collected samples of granitic rock from a 10 x 7 km area of the Bendeleben fault footwall block for (U-Th)/He analysis (Figure 3). Sample elevation ranged from 268 m near the scarp to 937 m in the interior of the batholith. One sample came from the Windy Creek pluton located east of the Bendeleben fault system in the foothills of the Darby Mountains.

Apatite was separated from samples using standard heavy liquid and magnetic separation at West Virginia University. Unfractured and inclusion-free apatite crystals were handpicked under a stereographic microscope and measured, in order to calculate α -ejection corrections [Farley, 2002; Ehlers and Farley, 2003]. Apatites were loaded in niobium tubes and then placed in a 46-well copper pan. Each apatite grain was degassed at 1000°C for 3 min and He concentration was measured by ^3He isotope dilution using a Balzers QMS 200 quadrupole mass spectrometer at the University of California, Santa Cruz. For apatite analyses, one of every five grains was analyzed with a second extraction (He re-extraction) to ensure complete degassing and to monitor for potential He release from more retentive undetected U and Th-bearing inclusions in analyzed apatite. After He measurements, apatite grains were spiked using a mixed ^{229}Th - ^{233}U tracer. Apatites were dissolved in concentrated HNO_3 for isotope-dilution inductively coupled plasma mass spectrometry (ICP-MS) analysis of U and Th on a Thermo Scientific X-series II quadrupole ICP-MS. Two fragments of Durango fluorapatite standard were analyzed along with our samples. Three to five grains were dated for each sample to assess reproducibility. Apatite ages were corrected for α -ejection using standard procedures of Farley [2002].

Fifteen samples yielded single-grain ages with low internal dispersion (Table 1). All the measured ages fall within the Paleogene with a weighted mean age of 41.3 ± 4.8 Ma (Eocene). The mean ages for individual samples range from 27.7 ± 5.4 Ma to 61 ± 15 Ma. Only samples BEN27 and BEN28 had a wide scatter of ages, possibly due to crystal flaws, inclusions, or instrumental error, and were excluded from interpretations. In a few cases, marked on Table 1, individual grain ages that are clear outliers were excluded from the calculation of the mean.

Table 1. Apatite (U-Th)/He Measured Ages

Sample	N Lat.	W Long.	Elev. (m)	U (ppm)	Th (ppm)	Th/U	4He (nmol/g)	Ft ^a	Corrected Age (Ma)	σ^b (Ma)	Assigned σ^c (Ma)	Weighted Mean Age ^d (Ma)	2 σ (Ma)	MSWD ^e
Bendeleben Pluton														
BEN09-3	65.1749	162.9114	268	1.1	2.2	2.12	4.16E-15	0.71	32.7	1.3	2.0	38.0	12.0	10.8
BEN09-2	65.1749	162.9114	268	1.2	2.5	2.09	1.09E-14	0.77	34.9	0.9	2.1			
BEN09-4	65.1749	162.9114	268	1	1.8	1.72	6.3E-15	0.72	46.1	2.1	2.8			
BEN09-1	65.1749	162.9114	268	8.9	24.9	2.8	4.25E-15	0.73	49.3	0.7	3.0			
BEN57-1	65.1786	162.8332	572	0.8	5.4	6.88	5.41E-15	0.72	29.1	0.9	1.7	33.1	7.7	5.9
BEN57-4	65.1786	162.8332	572	0.7	4	5.52	8.31E-15	0.77	30.9	0.9	1.9			
BEN57-2	65.1786	162.8332	572	1.2	5.1	4.13	1.13E-14	0.73	38.4	1.0	2.3			
BEN57-3	65.1786	162.8332	572	0.7	4.5	6.45	5.69E-15	0.71	38.6	1.0	2.3			
BEN28-2	65.1811	162.8699	755	8.1	48.4	6.02	9.45E-15	0.72	5.6	0.1	0.3	Poor Reproducibility		
BEN28-5	65.1811	162.8699	755	1.4	2.8	1.99	9.19E-15	0.71	71.9	2.5	4.3			
BEN28-1	65.1811	162.8699	755	1.5	7.7	5.11	1.64E-13	0.85	77.3	1.2	4.6			
BEN28-4	65.1811	162.8699	755	1.4	0.4	0.31	1.47E-14	0.75	90.7	3.8	5.4			
BEN28-3	65.1811	162.8699	755	1	0.3	0.31	1.89E-14	0.76	133.7	4.1	8.0	53.9	3.7	0.3
BEN56-2	65.1823	162.7844	543	1.6	8.6	5.51	2.63E-14	0.76	52.6	0.9	3.2			
BEN56-4	65.1823	162.7844	543	1.1	2.3	2.09	1.13E-14	0.75	53.6	1.3	3.2			
BEN56-3	65.1823	162.7844	543	0.8	3.2	3.84	1.39E-14	0.77	55.8	1.4	3.3			
BEN56-1	65.1823	162.7844	543	1	2	1.96	2.03E-14	0.79	63.3	4.7	3.8	Poor Reproducibility		
BEN27-1	65.1824	162.8628	759	1.2	2	1.71	1.78E-14	0.81	37.2	0.8	2.2			
BEN27-4	65.1824	162.8628	759	3.4	4.9	1.44	2.37E-14	0.75	46.9	1.2	2.8			
BEN27-3	65.1824	162.8628	759	1.6	3.1	1.98	2.01E-14	0.76	61.8	1.8	3.7			
BEN58-3	65.1867	162.8194	721	3.3	4.6	1.38	1.35E-14	0.69	54.8	1.7	3.3	60.1	14.0	2.5
BEN58-2	65.1867	162.8194	721	1.9	2	1.08	4.26E-15	0.63	62.1	2.8	3.7			
BEN58-4	65.1867	162.8194	721	1.2	2.2	1.83	6.95E-14	0.85	65.7	1.2	3.9			
BEN59-3	65.1928	162.8249	708	2.7	4.1	1.48	1.07E-14	0.71	39.6	0.8	2.4			
BEN59-2	65.1928	162.8249	708	3.7	5.2	1.42	7.01E-15	0.62	39.7	1.3	2.4	43.9	4.6	2
BEN59-5	65.1928	162.8249	708	2.2	4	1.77	1.95E-14	0.76	44.0	1.0	2.6			
BEN59-4	65.1928	162.8249	708	2.5	4.1	1.66	8.6E-15	0.67	46.9	1.5	2.8			
BEN59-1	65.1928	162.8249	708	2	4.1	2.04	2.6E-14	0.78	47.0	0.9	2.8			
BEN37-1	65.1992	162.7877	811	1.8	0.8	0.42	1.59E-14	0.77	54.2	1.5	3.3	59.0	17.0	3.5
BEN37-2	65.1992	162.7877	811	2.3	0.9	0.41	1.27E-13	0.86	58.7	1.0	3.5			
BEN37-3	65.1992	162.7877	811	2.5	1	0.39	1.38E-13	0.86	68.0	1.3	4.1			
BEN03-4	65.2029	162.8781	825	3.4	4.2	1.26	1.68E-14	0.72	41.1	1.0	2.5			
BEN03-3	65.2029	162.8781	825	3.2	4.9	1.56	1.71E-14	0.73	42.2	1.2	2.5	43.3	2.5	0.75
BEN03-2	65.2029	162.8781	825	1.7	2.3	1.39	1.8E-14	0.77	44.4	1.5	2.7			
BEN03-5	65.2029	162.8781	825	2	3	1.51	1.38E-14	0.75	46.2	1.2	2.8			
BEN24-2	65.2074	162.8483	937	1.7	2.5	1.45	5.8E-15	0.74	26.2	1.0	1.6			
BEN24-5	65.2074	162.8483	937	1.7	2.9	1.7	4.35E-15	0.71	26.2	1.1	1.6	27.2	4.9	1.5
BEN24-1	65.2074	162.8483	937	2	2.7	1.35	1.97E-14	0.80	29.8	0.9	1.8			
BEN24-3	65.2074	162.8483	937	3.1	4	1.3	1.14E-14	0.73	34.3	1.0	2.1			
BEN17-4	65.2085	162.9360	695	2.3	1.9	0.82	1.11E-14	0.73	46.7	1.3	2.8			
BEN17-1	65.2085	162.9360	695	4	7.9	1.99	1.09E-14	0.65	48.1	1.7	2.9	50.9	7.7	2.5
BEN17-5	65.2085	162.9360	695	2.9	2.8	0.95	7.83E-15	0.68	54.9	2.0	3.3			
BEN17-2	65.2085	162.9360	695	3.1	3.1	0.98	1.06E-14	0.68	56.7	1.8	3.4			
BEN42-1	65.2128	162.7926	920	1.9	5	2.63	1.8E-15	0.55	31.9	1.4	1.9			
BEN42-2	65.2128	162.7926	920	1.6	4.1	2.65	2.13E-15	0.61	33.2	1.6	2.0	34.1	8.5	2.7
BEN42-3	65.2128	162.7926	920	2.5	7.8	3.1	3.27E-15	0.55	38.7	1.5	2.3			
BEN30-4	65.2277	162.8240	687	1.9	3.6	1.86	5.78E-15	0.70	34.1	1.1	2.0			
BEN30-2	65.2277	162.8240	687	2.4	4.4	1.83	9.35E-15	0.72	37.6	1.1	2.3			
BEN30-1	65.2277	162.8240	687	1.9	3.2	1.72	5.06E-15	0.67	37.7	1.1	2.3	38.9	2.3	0.39
BEN30-3	65.2277	162.8240	687	3.6	6.3	1.73	7.42E-15	0.64	40.0	1.2	2.4			
BEN30-5	65.2277	162.8240	687	1.8	3.8	2.11	7.34E-15	0.69	40.4	1.7	2.4			
BEN29-1	65.2427	162.8575	868	0.3	0.3	1.33	1.35E-15	0.75	31.7	2.2	1.9			
BEN29-4	65.2427	162.8575	868	2.8	7.5	2.65	3.06E-15	0.62	36.1	1.0	2.2	36.5	7.3	4.3
BEN29-2	65.2427	162.8575	868	1.7	4.1	2.38	4.11E-15	0.66	39.4	1.8	2.4			
BEN29-5	65.2427	162.8575	868	3.1	5.1	1.68	6.3E-15	0.61	42.1	1.5	2.5			
Windy Creek Pluton														
BEN73-3	65.1510	162.5781	923	3.7	32.1	8.73	1.88E-14	0.61	51.1	1.3	3.1	54	19	52
BEN73-2	65.1510	162.5781	923	2.8	15.3	5.44	6.21E-14	0.77	49.5	0.8	3.0			
BEN73-1	65.1510	162.5781	923	9.4	22.3	2.36	6.02E-14	0.67	63.7	1.2	3.8			

^aF_{He} is the α -ejection correction after Farley (2002);

^b1 σ analytical uncertainty;

^cA more realistic uncertainty based on the reproducibility of the standards (6%);

^dWeighted mean age calculated excluding outlying ages which are crossed out on the table;

^eMean Weighted Standard Deviation, a measure of data dispersion.

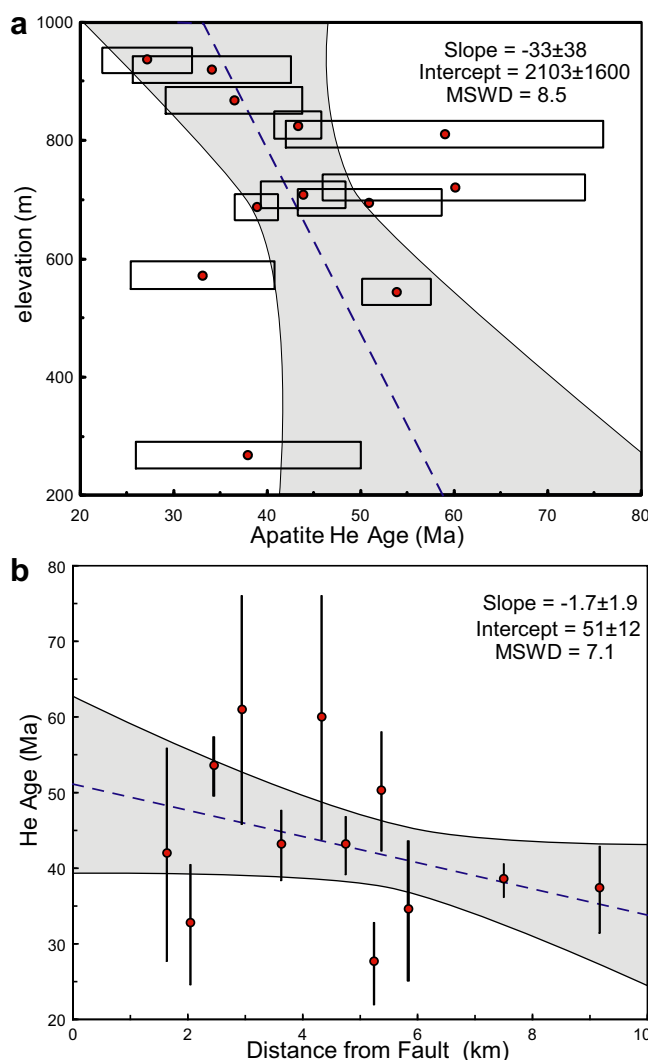


Figure 9. (a) Age versus elevation plot of apatite (U-Th)/He ages of the Bendeleben Mts. There is a statistically weak negative age-elevation correlation. (b) Plot of age versus distance from the Bendeleben fault. Samples collected closer to the fault are generally older than those further from the fault, but the correlation is also statistically weak. Lack of a strong correlation suggests that block uplift occurred with only minor tilting, and therefore the Bendeleben fault is likely steeply dipping.

(Figure 9). This suggests that if exhumation was driven by motion of the Bendeleben fault, as we believe, it was not accompanied by a large amount of footwall rotation.

4.3. HeFTy and Pecube t-T Modeling

HeFTy [Ketcham,] was used to evaluate the 1D thermal history of our apatite samples. Inverse Monte-Carlo modeling within HeFTy produces plausible, statistically robust, time-temperature (t-T) pathways. These are dependent upon the kinetic parameters of the apatite helium system of an individual grain and known geologic constraints on the thermal evolution. The model applied the diffusion kinetics of the Durango apatite calibration of Farley [2000] assuming a spherical geometry. In addition, we used the U-Pb emplacement ages of the Bendeleben pluton [Harris, 2011], biotite $^{40}\text{Ar}/^{39}\text{Ar}$ (BtAr) ages and closure temperature range, and the present-day mean surface temperature as t-T constraints. The modeled paths are assumed to be monotonic (consistent heating or cooling only) and were found after 10,000 Monte Carlo inversion runs.

Because the kinetics are affected by the specific grain dimensions and composition, we ran HeFTy models on a range of individual apatite grains including the youngest, mean, and oldest apatite helium ages from samples with low age dispersion and robust statistics in our data set. In Figure 10, we show the results for

There is a weak age-elevation relationship, with samples being younger at higher elevations, but the statistics of the correlation are poor (Figure 9). The weakness of this relationship is not surprising given that there is low footwall relief and the He ages are Paleogene and may not be strongly influenced by the recent landscape evolution. Samples with high internal age dispersion could be explained by variable eU concentration, which is a proxy for radiation damage effects on helium diffusivity, producing grain-specific kinetics and closure temperatures, as described by the RDAAM model (Flowers *et al.*, 2009). Our samples have undergone variable cooling rates and most recently, slow cooling and long residence in the apatite partial retention zone. This may explain the observed age dispersion. High heat flow and the presence of geothermal fluids in the Bendeleben region, as exemplified by the existence of hot springs and young basalt flows in Lava Creek, may also be responsible for puzzling age relationships due to partial helium loss via reheating. There is a poor statistical inverse correlation between bedrock helium ages and distance from the fault

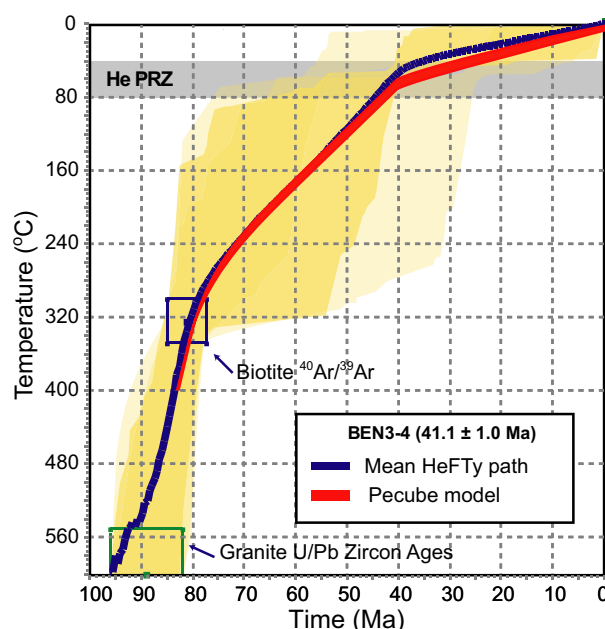


Figure 10. Time-temperature history calculated by inversion of apatite (U-Th)/He ages using the HeFTy model of Ketcham [2005] and Pecube [Braun, 2003]. Sample BEN3–4 is representative of the mean age of the data set. Dark yellow area represents the range of solutions that provide “good” fits with the constraints ($GOF > 0.9$). Light yellow area contains the “good” solutions to models for the youngest (BEN24–2) and oldest (BEN56–3) samples. The red line is the t-T history calculated by Pecube for the fault block model discussed in the text and shown in Figure 11. The gray band is the Partial Retention Zone of He in apatite. Boxes indicate t-T constraints imposed on the thermal history from zircon U-Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ data.

dome [Dumitru *et al.*, 1995]. The data are also compatible with the model of rapid cooling related to thinning over a rapidly ascending diapiric dome [Calvert *et al.*, 1999]. Our data does not provide strong control on the cooling history between 300 and 80°C (when samples enter the helium partial retention zone), as is evident from the broad envelope of possible cooling paths. The model for sample BEN3–4 shows a decline in the mean cooling rate to 6–7°C/Ma between 80 and 40 Ma, followed by even slower cooling (1–1.5°C/Ma) between 40 Ma and the present. The modeled t-T data from HeFTy suggest a cooling history where exhumation rates decrease as tectonic activity diminishes gradually through the Cenozoic. Contrary to our expectation, our AHe data do not detect the effect of recent unroofing related to the observed fault scarps.

Braun [2003] outlines how to use Pecube to understand the coupling between tectonics and erosion with the development of topography. Pecube is a finite-element code designed to solve the transient 3-D heat transport equation, including heat conduction, advection, and production in a crustal block. The effects of a finite amplitude, temporally variable topographic surface on the heat transport equation can also be explored. Pecube also incorporates movement along simple or complex faults and predicts age distributions for comparison with measured age data at each time step.

Our model incorporates a simplified geometry of the Bendeleben crustal block including block thickness, crustal density, the digital elevation model for the area (including the northern Darby Mountains), and specified thermal parameters (Table 2). The radiogenic heat production term within Pecube was not included in the modeling scenarios because values for this area are not well constrained. To account for the absence of radiogenic heat, a basal block temperature was set to 875°C. This imposes an initial geothermal gradient of ~25°C/km for the upper 5 km of the crust, which is the thermal zone of interest in apatite He dating. This does not imply that the crust is 875°C at 35 km depth, but is merely a way to produce the correct shallow thermal structure and promote stability of Pecube (geothermal gradient calculated from [Turcotte and Schubert, 1982]).

Figure 11 shows the final Pecube model results that match our measured apatite helium ages. A high-angle normal fault (dip of 75°S) is used in this model, although the actual dip of the Bendeleben fault is unknown. HeFTy modeling provided a guide to the likely timing of fault motion. Since we do not know the

sample BEN3–4 which we consider to be representative since its individual grain age (41 ± 1 Ma) matches the mean age of the data set as a whole. In addition, we show the envelope of t-T paths with better than 0.9 goodness of fit to the constraints for this sample (dark yellow), and for all the samples modeled (light yellow). The weighted-mean path may not be the statistically best cooling history, but it is representative of the overall model results.

All of the modeled samples show rapid cooling of ~20°C/Ma in the Late Cretaceous (95–80 Ma), as is required by the U-Pb granite emplacement ages and the biotite $^{40}\text{Ar}/^{39}\text{Ar}$ cooling ages. This supports the hypothesis of extensional unroofing of the Bendeleben metamorphic dome in a manner similar to the Kigluaik

Table 2. Pecube Modeling Parameters

Parameter	Model Input
Model duration	100 Ma
Number of time steps	1
Crustal block dimensions (x,y,z)	40 km × 40 km × 35 km
DEM grid spacing (x, y)	0.00027
Topographic amplification factor	1
Fault motion time intervals	3
Timing of exhumation rate change	100 start, 80, 40 Ma
Normal fault dip angle	75°S
Nodal points in z direction	35
Vertical node spacing	0.8 km
Thermal conductivity ^a	3.35 W m ⁻¹ K ⁻¹
Surface heat flow ^b	80–90 mW m ⁻²
Mantle heat flow	35 mW m ⁻²
Mantle density	3200 kg/m ⁻³
Crustal density	2700 kg/m ⁻³
Surface temperature z=0	0 C
Basal model temperature (z = 35) ^c	875 C
Initial geothermal gradient	25 C
Isostasy	0
Atmospheric lapse rate	6 C km ⁻¹
Heat production	0 C/Ma

^aMean thermal conductivity value for granitic rocks.

^bSurface heat flow from *Blackwell and Richards* [2004].

^cBasal temperature calculated in the absence of radiogenic heating. This is not realistic for the lower crust, but with a linear gradient, provides the correct surface heat flow and promotes model stability without negatively impacting shallow thermal structure.

paleoelevation history, topography remains at constant, modern elevations throughout the model. The normal faulting scenario shows maximum footwall exhumation rates that steadily decrease after fault initiation in the mid-Cretaceous. The normal fault is active in the model from 100 Ma to the present, at a rate of 0.9 mm/yr from 100 to 80 Ma, with changes in fault-induced exhumation to 0.21 mm/yr from 80 to 40 Ma and 0.06 mm/yr from 40 to 0 Ma. These faulting episodes are in agreement with the cooling history output in HeFTy. Pecube predicts that AHe and biotite Ar exhumed footwall ages are ~33–41 Ma and ~78–84 Ma, respectively. These values agree well with our mean measured ages.

Hudson and Plafker [1978] estimate a total post-Wisconsin displacement of 8 m on the Bendeleben normal fault, which is <1 mm/yr of displacement since the last major glacial event. Pecube modeled exhumation of 0.06 mm/yr since the mid-Eocene can be viewed as a time-averaged, conservative estimate of tectonic unroofing, which does not take into account any significant short-term changes in rates due to enhanced glacial erosion. Recent, glacially enhanced denudation producing sub-kilometer relief

would be indiscernible with low temperature AHe thermochronology and corresponding cooling models. The model shows that with this fault motion history the gradient in AHe ages adjacent to the fault is very narrow.

5. Regional Implications for Timing of Normal Faulting

In spite of the young fault scarps and active seismicity in the Bendeleben Mountains, our (U-Th)/He data and thermal models show that exhumation was most rapid in the Late Cretaceous to Early Tertiary, not in the Neogene or Quaternary.

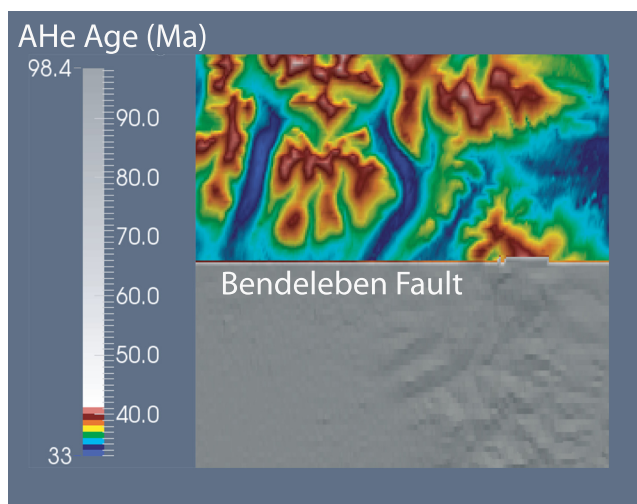


Figure 11. Map view of the final time step (30–0 Ma) of a Pecube model, which includes a steeply south-dipping fault and yields modeled apatite He ages that agree with measured ages from the Bendeleben Mountains. Location of figure is shown on Figure 1. There is a very narrow age gradient across the fault that we could not document in our sampling since there is no bedrock exposed along the fault itself or on the down-thrown block.

This cooling history and the inferred fault-driven exhumation history does correlate well with the timing of faulting deduced from seismic data from the off shore Hope Basin [*Elswick*, 2003; *Tolson*, 1987]. A good example of the Hope Basin structures can be seen on USGS seismic line 801 between shot points 600 and 1180 (Figure 12). The interpretation of the age of the stratigraphic sequences is based on correlation with the on-shore Cape Espenberg 1 and Nimiuk Point 1 wells on the eastern part of Kotzebue Sound [*Tolson*, 1987]. Time-depth conversion is also approximate, being based on stacking velocities

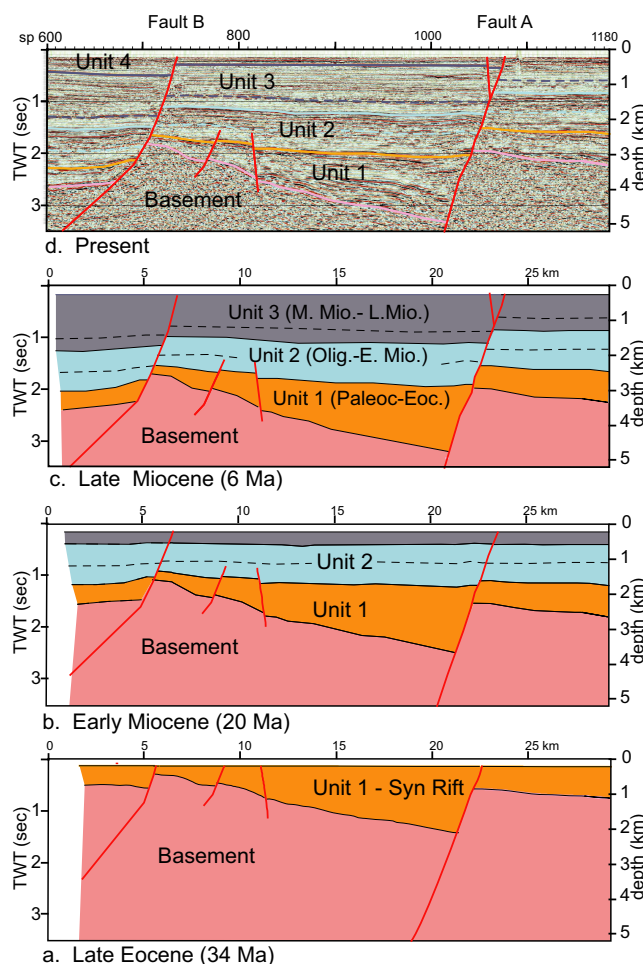


Figure 12. USGS reflection seismic line 801 (location shown in Figure 4) showing normal faults in the Early Tertiary Hope Basin in the Chukchi Sea, Northwestern Alaska [from *Elswick, 2003*]. Normal offset reveals an older stage (Eocene-Oligocene) of block tilting and rapid extension followed by slowing in fault activity during the Early Miocene and then a period of recent reactivation in the Late Miocene-Pliocene. This system is believed to be a part of the same extensional system governing exhumation of the Bendeleben Mountains. TWT = two way time.

only. Stratigraphic Unit 1 (probably Paleocene to Eocene) shows fanning of the seismic reflectors due to syn-sedimentary block rotation and up to 2 km of normal fault displacement in the Early Tertiary. Unit 1 strata in the wells are nonmarine and dominated by volcanoclastic deposits. In contrast, Unit 2 (Oligocene to Early Miocene?) has mostly parallel reflectors and experienced only minor fault offset during its deposition, suggesting a period of relative quiescence. Unit 3 (Middle to Late Miocene?) also has parallel reflectors and up to 0.5 km of faulting indicating renewed extension, which also affects Unit 4 (Pliocene to Holocene), since the faults reach the sea-floor. The Hope Basin normal faults range in orientation from E-W to NW-SE (Figure 4) and, in general, are consistent with fault orientations and direction of extension of the Bendeleben and Kigluaik faults. Therefore, they are likely part of the same early Cenozoic system and the on-shore Imuruk and McCarthy's Marsh basins are terrestrial equivalents to the offshore basins.

The driving mechanism for recent extension in the Seward Peninsula and the larger Bering Block appears to be an indirect response to the oblique North America-Pacific plate motions. The NW directed motion of Pacific plate with respect to North America causes large-magnitude dextral strike-slip along the Denali and Tintina fault systems in Alaska and convergence along the Alaska Peninsula and most of the Aleutian trench [Mackey *et al.*, 1997; Fujita *et al.*, 2002]. In western Alaska the blocks bounded by the major strike-slip faults are being extruded toward the Bering Sea. The pattern of modern earthquakes defines the boundaries of the rigid Bering Block (Figure 2), which is undergoing a clockwise rotation about a pole located in the Chukotka region of Northeastern Russia [Mackey *et al.*, 1997; Fujita *et al.*, 2002]. This clockwise motion is manifested by N-S extension in the Seward Peninsula, E-W convergence north of Kamchatka and strike-slip deformation in eastern Chukotka. It remains open to debate whether this same deformation pattern existed in the Early Tertiary when large magnitude extension was taking place in the Hope Basin and the Seward Peninsula. There is great uncertainty as to the direction of paleo-Pacific plate motions at that time because the location or geometry of the now subducted Kula-Pacific spreading ridge is poorly constrained [Engelbreton, *et al.*, 1985], but there is good geological evidence that in the Early Tertiary, western Alaska underwent significant oroclinal bending that produced the present day curvature of the Denali and Tintina faults [Plafker and Berg, 1994]. Also, by the Late Eocene, the subduction zone that existed along the southern margin of the Bering shelf had retreated south to the Aleutians, trapping a piece of paleo-Pacific oceanic crust and giving rise to a period

of extensional or transtensional basin formation on the Bering shelf [Worrall, 1991]. The Hope Basin specifically has been interpreted as a pull-apart basin that developed at the termination of the dextral Kobuk Fault. However this interpretation is problematic in that the length of the basin far exceeds that of the fault, and geological evidence for large magnitude dextral displacement along the Kobuk Fault is lacking.

6. Conclusions

Apatite fission-track and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of the exposed deep crustal rocks of the Kigluaik Mountains suggest that the existing thin crust of the Bering Region was established in the mid-Cretaceous but during the Early Tertiary a renewed period of faulting, offshore basin formation, and erosion occurred throughout the Seward Peninsula [Dumitru *et al.*, 1995; Tolson, 1987]. This renewed extensional signal can be seen in our measured AHe ages from the Bendeleben Mountains. The Tertiary tectonic regime can be modeled as episodic extension related to block rotations induced by tectonic extrusion in response to Pacific margin convergence and terrane accretion. Extension in the Seward Peninsula also corresponds to normal faulting in the Hope Basin, NW of the Seward Peninsula. We propose that these events are linked and are part of the same system. These results are in good agreement with regional tectonic and geochronologic information.

The weighted mean measured AHe age is 41.3 ± 4.8 Ma for the Bendeleben footwall block. Apatite (U-Th)/He, biotite $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology and thermal modeling has constrained the cooling and exhumation history of the central Seward Peninsula. Inverse HeFTy t-T modeling show that rapid cooling occurred in the mid-Late Cretaceous, after batholith emplacement, and has progressively slowed into recent time. HeFTy output t-T paths provide normal fault displacement inputs in Pecube forward models. Exhumation of the Bendeleben footwall block is estimated to be approximately 0.2–0.25 mm/yr from the late Cretaceous to Eocene and approximately 0.04–0.06 mm/yr from the Eocene to present.

Acknowledgments

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